2018

Carbon Footprint Assessment of Large-scale Pig Production System in Northern China: a Case Study

Yuanqing Zhou
Chinese Academy of Agricultural Sciences

Hongmin Dong
Chinese Academy of Agricultural Sciences

Hongwei Xin
Iowa State University, hxin@iastate.edu

Zhiping Zhu
Chinese Academy of Agricultural Sciences

Wenqiang Huang
Renmin University of China

See next page for additional authors

Abstract

China raises 50% of the global live pigs. However, few studies on carbon footprint (CF) of large-scale pig production based on China's actual production conditions have been carried out. In this study, life cycle assessment (LCA) method and actual production data of a typical large-scale pig farm in Northern China were used to assess greenhouse gas (GHG) emissions or CF associated with the whole process of pig production, including feed production (crop planting, feed processing, and transportation), enteric fermentation, manure management and energy consumption. The results showed a CF of 3.39 kg CO2-eq per kg of live market pig, and relative contributions of 55%, 28%, 13%, and 4% to the total CF by feed production, manure management, farm energy consumption, and enteric fermentation, respectively. Crop planting accounted for 66% of the feed production CF, while feed processing and transportation accounted for the remaining 34%. Long-distance transport of semi-raw feed materials caused by planting-feeding separation and over-fertilization in feed crop planting were two main reasons for the largest contribution of GHG emissions from feed production for the total CF. CF from nitrogen fertilizer application accounted for 33%-44% of crop planting, and contributed to 16% of the total CF. CF from transportation of feed ingredients accounted for 17% of the total CF. If the amount of nitrogen fertilizer used for producing the main feed ingredients is reduced from 209 kg/hm2 (for corn) and 216 kg/hm2 (for wheat) to 140 kg/hm2 (corn) and 180 kg/hm2 (wheat), respectively, the total CF would be reduced by 7%. If transportation distance for feed materials decreased from 325-493 km to 30 km, along with reducing the number of empty vehicles for the transport, total CF would be reduced by 18%. The combined CF mitigation potential for over-fertilization and transportation distance is 26%. In addition, use of pit storage – anaerobic digestion – lagoon practice can reduce GHG emissions from manure management by 76% as compared to the traditional pit storage – lagoon manure treatment method. This case study reveals the impact of planting-feeding separation and over-fertilization on CF of pig supply chain in China. Manure management practice of pit storage – anaerobic digestion – lagoon is much more conductive to reducing CF as compared to the traditional method of pit storage – lagoon.

Keywords

Life cycle assessment, Greenhouse gas, Pig, Mitigation

Disciplines

Agriculture | Animal Sciences | Bioresource and Agricultural Engineering | Meat Science

Comments

This is a manuscript of the article Zhou, Yuanqing, Hongmin Dong, Hongwei Xin, Zhiping Zhu, Wenqiang Huang, and Yue Wang. "Carbon Footprint Assessment of Large-scale Pig Production System in Northern China: a Case Study." *Transactions of the ASABE (in press)* (2018). DOI: 10.13031/trans.12805. Posted with permission.

Authors

Yuanqing Zhou, Hongmin Dong, Hongwei Xin, Zhiping Zhu, Wenqiang Huang, and Yue Wang

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

CARBON FOOTPRINT ASSESSMENT OF LARGE-SCALE PIG PRODUCTION SYSTEM IN NORTHERN CHINA: A CASE STUDY

Y. Q. Zhou, H. M. Dong, H. W. Xin, Z. Z. Zhu, W. Q. Huang, Y. Wang

The authors are **Yuanqing Zhou**, PhD Graduate Student, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences; **Hongmin Dong, ASABE Member Engineer**, Professor and Deputy Director, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences; **Hongwei Xin, ASABE Fellow**, Distinguished Professor, Department of Agricultural and Biosystems Engineering, Assistant Dean for Research, Iowa State University, Ames, Iowa; **Zhiping Zhu**, Professor, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences; The Key Laboratory of Energy Conservation and Waste Treatment of Agricultural Structures, Ministry of Agriculture, Beijing, China; **Wenqiang Huang**, Graduate student, School of Economics, Renmin University of China, Beijing; **Yue Wang**, Assistant Professor, Beijing Academy of Agriculture and Forestry Sciences. **Corresponding author**: Prof. Hongmin Dong, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences; The Key Laboratory of Energy Conservation and Waste Treatment of Agricultural Structures, Ministry of Agriculture, No. 12 Southern Street of Zhongguancun, Haidian District, Beijing 100081, China; Phone/Fax: 86-10-82109979; e-mail: donghongmin@caas.cn

ABSTRACT.

China raises 50% of the global live pigs. However, few studies on carbon footprint (CF) of large-scale pig production based on China's actual production conditions have been carried out. In this study, life cycle assessment (LCA) method and actual production data of a typical large-scale pig farm in Northern China were used to assess greenhouse gas (GHG) emissions or CF associated with the whole process of pig production, including feed production (crop planting, feed processing, and transportation), enteric fermentation, manure management and energy consumption. The results showed a CF of 3.39 kg CO_2-eq per kg of live market pig, and relative contributions of 55%, 28%, 13%, and 4% to the total CF by feed production, manure management, farm energy consumption, and enteric fermentation, respectively. Crop planting accounted for 66% of the feed production CF, while feed processing and transportation accounted for the remaining 34%. Long-distance transport of semi-raw feed materials caused by planting-feeding separation and over-fertilization in feed crop planting were two main reasons for the largest contribution of GHG emissions from feed production for the total CF. CF from nitrogen fertilizer application accounted for 33%-44% of crop planting, and contributed to 16% of the total CF. CF from transportation of feed ingredients accounted for 17% of the total CF. If the amount of nitrogen fertilizer used for producing the main feed ingredients is reduced from 209 kg/hm^2 (for corn) and 216 kg/hm^2 (for wheat) to 140 kg/hm^2 (corn) and 180 kg/hm^2 (wheat), respectively, the total CF would be reduced by 7%. If transportation distance for feed materials decreased from 325-493 km to 30 km, along with reducing the number of empty vehicles for the transport, total CF would be reduced by 18%. The

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

combined CF mitigation potential for over-fertilization and transportation distance is 26%. In addition, use of pit storage – anaerobic digestion – lagoon practice can reduce GHG emissions from manure management by 76% as compared to the traditional pit storage – lagoon manure treatment method. This case study reveals the impact of planting-feeding separation and over-fertilization on CF of pig supply chain in China. Manure management practice of pit storage – anaerobic digestion – lagoon is much more conductive to reducing CF as compared to the traditional method of pit storage – lagoon.

Keywords.

Life cycle assessment, Greenhouse gas, Pig, Mitigation

INTRODUCTION

Livestock sector accounts for 18% of the global greenhouse gas (GHG) emissions (de Vries and de Boer, 2010; Steinfeld et al., 2006). Nearly half of the global pigs are raised in China (FAOSTAT, 2015). As such pork is the main GHG source of China’s food supply chain (Xu and Lan, 2016). Therefore, scientific evaluation of carbon footprint (CF) for China's pig production is important to the analysis of emission sources and policy-making on mitigation measures.

Life cycle assessment (LCA) method has been used to build GHG or CF emission assessment models of livestock sectors for different regions and production scales. Examples include global GLEAM model (MacLeod et al., 2013), European CAPRI model (Lesschen et al., 2011; Weiss and Leip, 2012), Canadian ULICEES model (Vergé et al., 2016), and SustainPork® model for farm (Noya et al., 2016). On the basis of IPCC (2006) calculation formula, results of these models were presented in different functional units using allocations of mass, economic value, protein, etc. Adaptive database was fit for each model. For example, parameters of GLEAM model were derived from international organizations such as Statistics Division of Food and Agriculture Organization of United Nations (FAOSTAT) and United Nations Framework Convention on Climate Change (UNFCCC) (MacLeod et al., 2013). The parameters of CAPRI model were derived from European Union Statistics (EUROSTAT) and data of the nitrogen excretion were taken from the GAINS database for EU (Lesschen et al., 2011; Weiss and Leip, 2012). The parameters of ULICEES model were derived from the Canadian Department of Agriculture Statistics data (Vergé et al., 2016). The calculation process for SustainPork® model was more detailed and based on production parameters of the farm (Noya et al., 2016).

Based on the above models and databases, CF assessment of pig production in different scales or addressing different concerns has been carried out. Basset-Mens and Van der Werf (2005) and Kool et al. (2009) compared effects of organic and

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

conventional pig production chain on CF. Lesschen et al. (2011) used CAPRI model to analyze CF of EU livestock products, emphasizing the impact of land use change on CF. Pelletier et al. (2010) focused on comparison of CF based on slat floor-based swine production systems and deep-bedded niche swine production systems. Cederberg (2004) evaluated pork CF in Sweden, based on LCA method and used economic allocation in the study of animal welfare, environmental impacts and product quality for pig farming. Vergé et al. (2016) and Noya et al. (2016) analyzed effects of allocation methods and functional units on CF assessment of individual farms. These studies provide valuable references for assessing CF of pig production in China, although they used location specific database or parameters in the respective CF assessment. However, considerable differences exist between western countries and China in manure management and crop planting for pig production. These differences lie in the in-house manure handling practices, outdoor manure storage (use of anaerobic digestion or direct land application), the amount of commercial fertilizer vs. animal manure used in crop production (more commercial fertilizer tends to be used in China), separation distance of geographical locations for feed crop production and swine farms (farther apart in China), and the level of mechanization in crop farming (less degree of mechanization in China). Consequently, the parameters used in the cited studies do not reflect the characteristics of pig production in China, and neither can the results be directly used to support policy-making about GHG mitigating measures for Chinese pig production systems.

CF assessment of Chinese pig production systems has just started. Jianyi et al. (2015) and Xu and Lan (2016) used LCA method to evaluate CF of Chinese pork production in the context of CF assessment of the Chinese food production. Jianyi et al. (2015) focused on assessing the variations of CF of Chinese food including pork production for three decades (1979-2009). Xu and Lan (2016) compared differences in CF between 22 plant-based foods and 6 animal-based foods. Both cases did not provide details of emissions at different stages and mitigating measures for pig production, and lacked detailed analysis for the higher CF caused by excessive fertilizer application and long-distance feedstuffs transportation in China as compared with EU and America. Luo et al. (2015) assessed CF of household and aggregated pig production in Sichuan Province, China, based on a survey of 32 pig farms in Hongya country. But there was no clear description about the characteristics of feed production or manure management. Results of these two studies were inconsistent with each other. Luo et al. (2015) and Xu and Lan (2016) showed that feed production contributed the greatest to GHG emissions of pig production systems in 2012 and 2013, respectively; whereas Jianyi et al. (2015) found that for 2009 GHG emissions from manure management far exceeded that from feed production in China. With the rapid development of large-scale livestock production in China, where most of the large-scale pig farms are using industrial feeding systems, there is no own land for feed crop planting or manure application (Bai et al., 2014). It is therefore necessary to assess GHG emissions based on actual pig production conditions in China, and to analyze sources of GHG emissions from large-scale pig production systems, and to explore potential mitigating measures.

In this study, a large-scale pig farm in Northern China was selected as a typical case for the CF assessment. The aim of this study was to quantify GHG emissions and relative contributions by each sector throughout the pig production chain and to explore potential CF mitigating measures. Results of the study are expected to provide scientific data on CF baseline, potetnial CF mitigating measures, and policy-making for pig production in China.

METHODS

In this study, LCA method was used to study a typical large-scale pig farm located in Hebei Province, China (37º-38ºN, 115º-116ºE). Annual average temperature at the pig farm location was 12.4℃ in 2015, the year this LCA study was based on. The main breeds of the pigs were Landrace and Large White. The total on-farm swine inventory was 85,210; including 7,200 sows, 18,850 nursery pigs, and 59,160 fattening pigs.

Three types of GHG were assessed: CO_2, CH_4, N_2O, with a respective 100-year horizon global warming potential of 1, 25, 298 (IPCC, 2007).

SYSTEM BOUNDARY

The accounting scope of GHG emissions ranged from feed production to farm gate in this study. The system boundary is shown in Fig.1, including feed production module and animal production module. The feed production module consisted of fertilizer production and transportation, agricultural film and pesticide production, energy consumption for irrigation and agricultural machinery, fertilizer application, and feed processing and transportation. The animal production module consisted of enteric fermentation, manure management, and farm energy consumption.

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

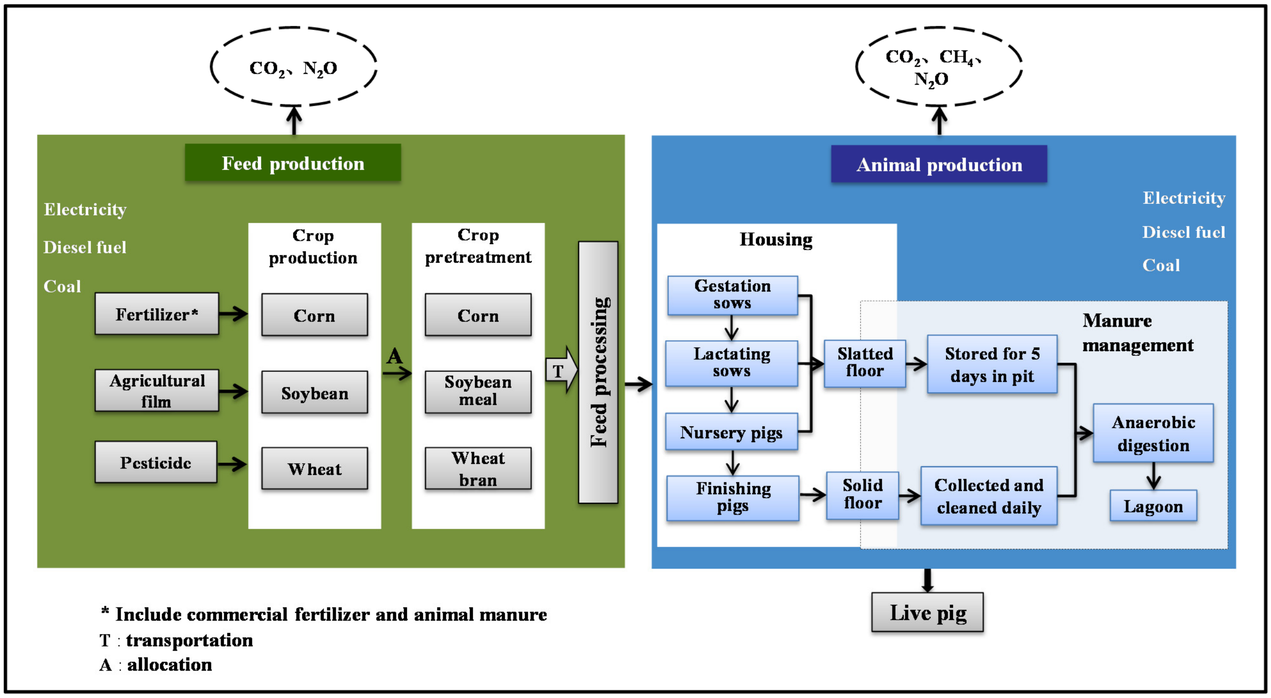

Fig. 1. System boundary of the pig production in this carbon footprint assessment.

For the raw materials of feed on the farm, corn accounted for 63%, soybean meal 18%, wheat bran 12%, and other components (such as soya oil, fish meal, wheat flour, calcium hydrophosphate, salt, glucose, and lysine) about 7%. This study just calculated GHG emissions from the three major feedstuffs (corn, soybean meal and wheat bran). Emissions from land use change, soil carbon, and infrastructures related to production such as farm construction and equipment manufacturing are outside the system boundary. Hence, these emissions were excluded in the CF assessment.

Functional Unit and Allocation

In this study, 1kg live weight (LW) was chosen as the functional unit. The choice of different allocation methods has large impact on the results of CF assessment. ISO14044 recommendations state that in principle, allocation should be avoided; if the allocation cannot be avoided, system expansion should be chosen preferentially (ISO, 2006). In this study, taking into account the volatility of market price of feed crop products, mass allocation was used for GHG emissions allocation between main and by-product of feed crops. The proportion of GHG emissions allocated to the corn grain relative to the total corn crop was 60%, and the value was 32% for soybean meal and 25% for wheat bran (Bi et al., 2009).

GHG Emissions Calculation

The equations for calculating GHG emissions from farm sources are shown in Table 1. The calculation of fuel consumption of transportation was derived from Lineng et al. (2003). The study assumes that a) all the transportation uses

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

diesel trucks; b) a complete transport task includes a vehicle of no-load or full-load; c) a partial journey transportation is treated as a full journey.

The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

Table 1. Sources of GHG emission and calculation equations.

Emission source	Calculation equation	Definition	Reference
Feed production			
1. Agricultural film (af)---CO_2	$CO_{2(feed,af)} = \sum_i S_i \times EF_{af} \times AP_{(feed\,i,af)}$	$CO_{2(feed,af)}$ is CO_2 emissions from agricultural film use (kg CO_2); i is species/category of feed crop; S_i is the area of the feed crop (hm^2); EF_{af} is emission factor for agricultural film production (kg CO_2/kg); $AP_{(feed\,i,af)}$ is amount of agricultural film application (kg/hm^2).	
2. Pesticide---CO_2	$CO_{2(feed,pest)} = \sum_i S_i \times EF_{pest} \times AP_{(feed\,i,pest)}$	$CO_{2(feed,pest)}$ is CO_2 emissions from pesticide input (kg CO_2); EF_{pest} is emission factor for pesticide production (kg CO_2/kg); $AP_{(feed\,i,pest)}$ is amount of pesticide application (kg/hm^2).	
3. Irrigation---CO_2	$CO_{2(feed,irrig)} = \sum_i S_i \times EF_{electric} \times AP_{(feed\,i,electric)}$	$CO_{2(feed,irrig)}$ is CO_2 emissions from irrigation (kg CO_2); $EF_{electric}$ is emission factor for electricity (kg CO_2/kwh); $AP_{(feed\,i,electric)}$ is amount of electricity used for irrigation (kwh/hm^2).	
4. Farm machinery---CO_2	$CO_{2(feed,machine)} = \sum_i \left(\frac{\frac{T_i}{R_i} \times 100}{Y_i}\right) \times EF_{diesel} \times AP_{(feed\,i,diesel)} \times \rho_{diesel}$	$CO_{2(feed,machine)}$ is CO_2 emissions from farm machinery (kg CO_2); T_i is annual consumption of feed (kg); Y_i is the yield of crop species/category i (kg/hm^2); EF_{diesel} is emission factor of diesel (kg CO_2/kg); $AP_{(feed\,i,diesel)}$ is coefficient of fuel consumption for farm machinery (L/hm^2); ρ_{diesel} is diesel density (kg/L).	
5. Fertilizer-N_2O-direct	$N_2O_{D(land,fer)} = \sum_i S_i \times AP_{(feed\,i,N)} \times EF_{Dferti} \times \frac{44}{28}$	$N_2O_{D(land,fer)}$ is direct N_2O emissions from fertilizer application (kg N_2O/year); $AP_{(feed\,i,N)}$ is amount of pure nitrogen application from fertilizer input (kg/hm^2); EF_{Dferti} is emission factor for direct N_2O emissions from N inputs (kg N_2O-N/kg N input); $\frac{44}{28}$ is conversion of (N_2O-N) emissions to N_2O emissions.	IPCC (2006)
6. Fertilizer-N_2O-indirect	$N_2O_{ID(land,fer)} = \sum_i S_i \times AP_{(feed\,i,N)} \times (EF_{GASM} \times Frac_{GASM} + EF_{LEACH-(H)} \times Frac_{LEACH-(H)}) \times \frac{44}{28}$	$N_2O_{ID(land,fer)}$ is indirect N_2O emissions from fertilizer application (kg N_2O/year); EF_{GASM} is emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N-N_2O/kg NH_3-N+NO_x-N volatilised); $Frac_{GASM}$ is fraction of synthetic fertilizer N that volatilises as NH_3 and NO_x (kg N volatilised/kg N applied); $EF_{LEACH-(H)}$ is emission factor for N_2O emissions from N leaching and runoff (kg N_2O-N/kg N leached and runoff); $Frac_{LEACH-(H)}$ is fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N/kg N applied).	IPCC (2006)
7. Urea use---CO_2	$CO_{2(land,urea)} = \sum_i S_i \times EF_{urea} \times AP_{(feed\,i,urea)} \times \frac{44}{12}$	$CO_{2(land,urea)}$ is CO_2 emissions from urea application (kg CO_2); EF_{urea} is emission factor of urea (kg C/kg urea); $AP_{(feed\,i,urea)}$ is amount of urea application (kg/hm^2); $\frac{44}{12}$ is conversion of (CO_2-C) emissions to CO_2 emissions.	IPCC (2006)
8. Transportation---CO_2	$CO_{2(fer,trans)} = \sum_t \left\{EF_{diesel} \times \left[\left(\frac{g_1}{v_1} + \frac{g_0}{v_0}\right) \times VSP\right] \times L \times m_t \times \left[\sum_t \left(\frac{M_t}{m_t}\right) \times 2\right]\right\}$	$CO_{2(fer,trans)}$ is CO_2 emissions from transportation (kg CO_2); g_1 is the fuel consumption rate of vehicle in full-load (t/kwh); g_0 is the fuel consumption rate of vehicle in no-load (t/kwh); v_1 is speed of vehicle in full-load (km/h); v_0 is speed of vehicle in no-load (km/h); VSP is specific power of vehicle (kw/t); L is transport distance (km); m_t is carrying capacity of the transport vehicle (t); M_t is the amount of fertilizer/feed (t).	Lineng et al. (2003)
Pig production			
9. Enteric fermentation---CH_4	$CH_{4(farm,enteric)} = \sum_T \left(\frac{DMI_T \times 18.45 \times \left(\frac{Y_{m,T}}{100}\right) \times 365}{55.65}\right) \times N_T$	$CH_{4(farm,enteric)}$ is CH_4 emissions from enteric fermentation (kg CH_4); T is species/category of livestock; DMI is dry matter intake (kg/day); $Y_{m,T}$ is methane conversion factor; N_T is the number of head of livestock species/category T in the system; 18.45 is conversion factor for dietary gross energy intake per kg of dry matter (MJ/kg); 55.65 is the energy content of methane (MJ/kg CH_4).	IPCC (2006)

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed.
Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

10. Manure management---CH_4	$CH_{4(farm,ms)} = \sum_T \left(\left[GE \cdot \left(1 - \frac{D}{100}\right) + (UE \cdot GE)\right] \cdot \left[\left(\frac{1-ASH}{18.45}\right)\right] \cdot 365\right) \cdot \left[B_{O(T)} \cdot 0.67kg/m^3 \cdot \sum_{S,k} \frac{MCF_{S,k}}{100} \cdot MS_{(T,S,k)}\right] \times N_T$	$CH_{4(farm,ms)}$ is CH_4 emissions from manure management (kg CH_4); GE is gross energy intake (MJ/day); D is digestibility of the feed (%); $UE \cdot GE$ is urinary energy expressed as fraction of GE; ASH is the ash content of manure; $B_{O(T)}$ is maximum methane producing capacity for manure (m^3 CH_4/kg VS); 0.67 is conversion factor of m^3 CH_4 to kg CH_4; $MCF_{S,k}$ is methane conversion factors for each manure management system S by climate region k (%); $MS_{(T,S,k)}$ is fraction of livestock category T manure handled using manure management system S in climate region k; S is manure management system; 365 is basis for calculating annual volatile solids production.	IPCC (2006)
11. Manure management-N_2O-direct	$N_2O_{D(farm,ms)} = \left[\sum_S \left[\sum_T \left(N_{(T)} \cdot Nex_{(T)} \cdot MS_{(T,S)}\right)\right] \cdot EF_{D(manure,N_2O,S)}\right] \cdot \frac{44}{28}$	$N_2O_{D(farm,ms)}$ is direct N_2O emissions from manure management (kg N_2O/day); $Nex_{(T)}$ is annual average N excretion per head of species/category T (kg N_2O/head/year); $MS_{(T,S)}$ is fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S; $EF_{D(manure,N_2O,S)}$ is emission factor for direct N_2O emissions from manure management system S (kg N_2O-N/kg N excreted).	IPCC (2006)
12. Manure management-N_2O-indirect (volatilization)	$N_2O_{G(farm,ms)} = \sum_S \left[\left[\sum_T \left(N_{(T)} \cdot Nex_{(T)} \cdot MS_{(T,S)}\right) \cdot \left(\frac{Frac_{GasMS}}{100}\right)_{(T,S)}\right]\right] \cdot EF_{IN-G(manure,N_2O,S)} \cdot \frac{44}{28}$	$N_2O_{G(farm,ms)}$ is indirect N_2O emissions due to volatilization of N from manure management (kg N_2O/day); $Frac_{GasMS}$ is percent of managed manure nitrogen that volatilises as NH_3 and NO_x in the manure management system (%); $EF_{IN-G(manure,N_2O,S)}$ is emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces (kg N_2O-N/(kg NH_3-N+ NO_x-N volatilised)).	IPCC (2006)
13. Manure management-N_2O-indirect (leach)	$N_2O_{L(farm,ms)} = \sum_S \left[\left[\sum_T \left(N_{(T)} \cdot Nex_{(T)} \cdot MS_{(T,S)}\right) \cdot \left(\frac{Frac_{L-MS}}{100}\right)_{(T,S)}\right]\right] \cdot EF_{IN-L(manure,N_2O,S)} \cdot \frac{44}{28}$	$N_2O_{L(farm,ms)}$ is indirect N_2O emissions due to leaching and runoff from manure management (kg N_2O/day); $Frac_{L-MS}$ is percent of managed manure nitrogen losses due to runoff and leaching during solid and liquid storage of manure (%); $EF_{IN-L(manure,N_2O,S)}$ is emission factor for N_2O emissions from nitrogen leaching and runoff (kg N_2O-N/kg N leached and runoff).	IPCC (2006)

DATA SOURCE

Following IPCC (2007) guidelines, when available, published data reflecting domestic production practices were used as the parameters for GHG emissions calculation in this study. When not available, data according to expert recommendations or through indirect calculation were used. The details are described below.

Production Data

In this study, data related to animal production in the CF calculation were obtained through on-site survey. The main herd parameters of the pig farm are shown in Table 2.

Table 2. Main herd parameters of the pig farm.

Pig stage	Value	Unit
Sows		
Number of sows	7,200	head
Gestation period	114	day
Number of piglets weaned per litter	11	head
Lactation period	28	day
Piglets		
Body weight at birth	1.5	kg
Body weight at weaning	8.0	kg
Weaning pigs		
Nursery phase period	42	day
Initial body weight in nursery phase	8	kg
Final body weight in nursery phase	25	kg
Growing-finishing pigs		
Number of growing-finishing pigs	59,160	head
Grow-finish phase period	120	day
Initial body weight in finishing phase	25	kg
Final (market) body weight	110	kg
Feed conversion ratio	2.68	

Feed Production

The corn, soybean meal and wheat bran considered in this study were produced respectively in Jinzhong City, Shanxi Province, Linyi City, Shandong Province and Shenzhou City, Hebei Province.

The required data for the GHG emission calculation were acquired according to the National Data Compilation of Revenue and Cost of Agricultural Products (NDRC, 2016) by referring to and recalculating the statistical data of the corresponding region and the corresponding year (Table 3).

Table 3. Average yields and agricultural material inputs of feed crops [a].

Category	Corn	Soybean	Wheat	Unit	Notes
Yield	8.5042	2.5839	6.8515	t/hm^2	
Commercial N fertilizer	0.1137	0.0315	0.1694	t/hm^2	
Nitrogen of commercial compound fertilizer	0.0396	0.0109	0.0413	t/hm^2	Assume N:P:K = 15:15:15
Urea	0.1066	0.0315	0.1542	t/hm^2	
Nitrogen of animal manure	0.0553	0.0105	0.0053	t/hm^2	Assume the price of 1 ton manure is 200 yuan [b], and the nitrogen content is 3% by weight.
Commercial P fertilizer	0.0027	0.0043	0.0028	t/hm^2	
Commercial K fertilizer	0.0031	0.0045	0.000597	t/hm^2	
Commercial compound fertilizer	0.2639	0.0725	0.2755	t/hm^2	
Diesel fuel used for agricultural machinery	61.6528	16.6998	73.6097	L/hm^2	The price per liter of diesel fuel is 5.4 yuan*, and the diesel fuel accounts for 20% of the machinery costs.
Electricity used for irrigation	794.7761	196.3261	1791.6188	kwh/hm^2	The price per kilowatt hour of agricultural electricity is 0.52 yuan*
Agricultural film	7.3134	0	0	kg/hm^2	
Pesticide	2.1158	2.7104	3.5182	kg/hm^2	
Transport distance	325	493	30	km	

[a] Recalculated from National Data Compilation of Revenue and Cost of Agricultural Products (NDRC, 2016).

[b] 1 U.S. dollar ≈ 6.6 yuan.

In order to make the results of calculation more representative of and suitable for pig production in China, GHG emission factors related to production, transportation and use of fertilizers, agricultural film, pesticides, agricultural diesel, and coal during feed production were taken from the domestic studies (Chen et al., 2015; Wang et al., 2015). The emission factors of Northern China power grid were chosen to calculate emissions form electricity consumption (NDRC, 2013) (Table 4).

Table 4. GHG emission factors of fertilizer production, application and other inputs under China conditions

Category	Value	Unit	Reference
N fertilizer	2.116	kg CO_2-eq/ kg N	Chen et al. (2015)
P fertilizer	0.636	kg CO_2-eq/ kg P_2O_5	Chen et al. (2015)
K fertilizer	0.180	kg CO_2-eq/ kg K_2O	Chen et al. (2015)
Compound fertilizer	0.067	kg CO_2-eq/ kg	Estimated value [a]
Agricultural film	22.72	kg CO_2-eq/ kg	Wang et al. (2015)
Pesticide	12.44	kg CO_2-eq/ kg	Wang et al. (2015)
Coal	1.98	kg CO_2-eq/ kg	China Energy Statistical Yearbook (2016)
Diesel fuel (highway)	3.16	kg CO_2-eq/ kg	China Energy Statistical Yearbook (2016)
Electricity	0.8843	kg CO_2-eq/ kwh	NDRC (2013)
N_2O emitted from the various synthetic and organic N applications to soils	0.01	kg N_2O-N/ kg N applied	IPCC (2006)
Coefficient of volatilised N from synthetic fertilizer	0.1	(kg NH_3-N+NO_x-N)/kg N applied	IPCC (2006)
Coefficient of N lost through leaching/runoff	0.3	(kg N leaching/runoff)/kg N applied	IPCC (2006)

[a] A fertilizer plant with annual outputs of 200,000 ton consumes 4 million kilowatt-hours of electricity and 5,000 ton of coal.

Manure Management

Manure in the gestation, lactating sows/piglets and nursery houses with slatted floor was collected in the pit and stored for about 5 days before removed. Manure in the fattening pig houses with solid floor was collected in a gutter outside the pig house and removed daily. There was no solid-liquid separation of the manure. In all cases pig manure was transported to the on-site biogas plant for biogas production, and the biogas digester effluent was pumped into the lagoon. Subsequently the lagoon effluent was transported through underground pipe to the local county wastewater treatment center, where it was processed together with other industrial wastewater and urban sewage. In the calculation of N_2O emissions from manure management, the nitrogen excretion (Nex) rate was based on the data provided in the First National Pollution Census Bulletin of the People's Republic of China (CNEPA, 2010). The Nex rate of each category of pigs was 33 g N/head/day for fattening pigs, 20 g N/head/day for piglets, 44 g N/head/day for sows. The emission factors required to calculate GHG emissions from manure management were derived from default values of IPCC (2006). The specific values are shown in Table 5.

Table 5. GHG emission factors of manure management.

Category	Pit storage	Anaerobic digestion	Lagoon	Unit	Reference
Methane conversion factor	0.03	0.1 [a]	0.7		IPCC (2006)
Emission factors for direct N_2O emissions from manure management	0.002	0	0	kg N_2O-N/kg nitrogen excreted	IPCC (2006)
N loss from manure management due to volatilisation of N-NH_3 and N-NO_x	20	20	40	%	IPCC (2006)
Total N loss from manure management	25	20	78	%	IPCC (2006)
Factors of volatilised and re-deposited N	0.01	0.01	0.01	kg N_2O-N/(kg NH_3-N+ NO_x-N volatilised)	IPCC (2006)
Factors of N lost through leaching/runoff	0.0075	0.0075	0.0075	kg N_2O-N/(kg N leaching/runoff)	IPCC (2006)

[a] CH_4 leakage during storage of digested manure.

Manure management process of the farm made it a composite system due to different duration of manure storage. As such VS and Nex are consumed in each stage of manure management. The VS and Nex consumption rate during the in-house pit storage was 3% and 11%, respectively (IPCC, 2006; Wang et al., 2017). In comparison, the VS and Nex consumption rate during anaerobic digestion was 70% and 5%, respectively (Nasir et al., 2012; Zhang et al., 2014; Wang et al., 2017).

Transportation

When calculating GHG emissions from the transportation in this study, it was assumed that the transport vehicle has a carrying capacity of 5 t, and that it travels at 60 km/h with no load and 45 km/h with full load.

Calculation of the CF for various components and the total supply chain were performed in Excel spreadsheet.

Energy comsumption

The type of energy used on the pig farm mainly included electricity and diesel fuel. The annual amount of electricity and diesel consumption was, respectively, 9,671 MWh/yr and 18 t/yr.

RESULTS AND DISCUSSION

CF OF PIG PRODUCTION SYSTEM

The annual GHG emissions from the pig supply chain were estimated to be 53,225 t CO_2-eq and the CF was 3.39 kg CO_2-eq/kg LW. From a global perspective, CF per kg pork varies considerably, ranging from 2.3 to 8.7 kg CO_2-eq due to differences in system boundary, allocation method, functional unit, manure management, and so on (Table 6). The French good agricultural practice for pig production system was shown to have the smallest CF of 2.3 kg CO_2-eq/kg LW (Basset-Mens and Van der Werf, 2005). In comparison, Noya et al. (2016) included GHG emissions from the slaughter and processing stages as well as feed production and animal production, and made no distinction in GHG allocation between the main and by-products of feed crop, which led to the largest CF of 6.09 kg CO_2-eq/kg LW or an equivalent of 8.7 kg CO_2-eq/kg CW (CW = carcass weight, LW to CW ratio = 0.7).

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed.
Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

Table 6 Comparison of carbon footprint of pig production among various studies.

Source	Country / Region	System boundary	Allocation method	Functional unit (FU)	CF (kg CO_2-eq/kg FU)
This study	China (Hebei)	From feed production to farm gate	Mass allocation	LW	3.39
MacLeod et al. (2013)	Global	From feed production to retail	Economic value	CW	6.07
Luo et al. (2015)	China (Sichuan)	From feed production to farm gate	---[a]	CW (LW)	4.29 (3.00) [b]
Cederberg (2004)	Sweden	From feed production to farm gate	Economic value	One kg of bone and fat free meat	3.6
Dalgaard et al. (2007)	Denmark	From feed production to slaughter	System expansion	CW	3.6
Nguyen et al. (2011)	Denmark	From feed production to slaughter	Economic value	CW	3.4
Kool et al. (2009)	Netherland	From feed production to farm gate	Economic value	CW (LW)	3.6 (2.52)
Basset-Mens and Van der Werf (2005)	France	From feed production to farm gate	Economic value	LW	2.3
Reckmann et al. (2013)	Germany	From feed production to slaughter	Economic value	CW	3.22
González-García et al. (2015)	Portugal	From feed production to farm gate	No allocation	LW	2.6
Noya et al. (2016)	Spain	From feed production to slaughter	No allocation	LW/CW	6.7/8.7
Lesschen et al. (2011)	European Union(27)	From feed production to farm gate	System expansion	CW (LW)	3.5 (2.45) [n-LUC], 5.37 (3.7) [LUC]
Weiss and Leip (2012)	European Union(27)	From feed production to farm gate	System expansion	CW (LW)	4.46 (3.12) [n-LUC], 5.79 (5.22) [LUC]
Vergé et al. (2016)	Canada	From feed production to slaughter	--- [c]	CW,	2.88-4.43
Pelletier et al. (2010)	United States	From feed production to farm gate	Energy allocation	CW (LW)	2.47 (1.7)
Wiedemann et al. (2016)	Australia	From feed production to farm gate	Economic value	LW	3.6

[a] No clear explanation.
[b] The CF in parentheses values were converted to LW per kg.
[n-LUC] Exclude GHG emissions from land use changes.
[LUC] Include GHG emissions from land use changes.
[c] Three different allocation methods.

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed.
Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

Although CF of pork could not be compared readily among different studies, we attempted to compare our study with those that had similar assessment scope of CF (from feed production to farm gate) and converted the functional unit from CW to LW with a CW to LW ratio of 0.7. CF observed in this study was close to the results of Luo et al. (2015) (3.0 kg CO_2-eq/kg LW) and Wiedemann et al. (2016) (3.6 kg CO_2-eq/kg LW), but was higher than that of Pelletier et al. (2010), Kool et al. (2009) and González-García et al. (2015) (Table 6). The following factors may explain the differences in emission intensity between this study and others. First, there are differences in emission sources for the same scope of feed production to farm gate. This study included CH_4 emissions from enteric fermentation during animal production, which was not considered in the study by Luo et al. (2015). Lesschen et al. (2011), Weiss and Leip (2012), Pelletier et al. (2010) and Kool et al. (2009) only calculated on-farm direct energy consumption, and did not include indirect energy consumption of feed transportation. Second, this study used mass allocation method for GHG emissions between main and by-product of feed crops, yielding a 32% distribution ratio of soybean meal. In comparison, Wiedemann et al. (2016) used economic value to allocate GHG emissions of main and by-product of feed crops, which yielded 62% allocation ratio for soybean meal, and a slightly higher CF of 3.6 kg CO_2-eq/kg LW. González-García et al. (2015) used system expansion method on pork supply chain to avoid repeated calculation of GHG emissions from the system modules. The result of CF was 2.6 kg CO_2-eq/kg LW, significantly lower than the result of our study. Furthermore, feed conversion ratio (FCR) is a key factor that influences CF assessment. In this study, FCR of the growing-finishing pig was 2.68. However, it was 2.44 in Pelletier et al. (2010) who reported a CF of 1.7 kg CO_2-eq/kg LW, half of the magnitude as found in our study. The FCR reported in Wiedemann et al. (2016) and Weiss and Leip (2012) were 3.1 and 4.1 respectively, and the corresponding assessment values (3.6 kg CO_2-eq/kg LW, 5.2 kg CO_2-eq/kg LW) were larger than that of our study. Other parameters used in the calculation could also influence the results. For instance, emission factor of electricity power in Northern China was 0.8843 kg CO_2-eq/kwh, versus 0.92 kg CO_2-eq/kwh used in Luo et al. (2015) which was higher than the national average. In this particular case, use of 0.8843 kg CO_2-eq/kwh vs. 0.92 kg CO_2-eq/kwh led to a CF difference of 4%.

CONTRIBUTIONS AND POTENTIAL MITIGATION OF DIFFERENT STAGES

The results showed that the CF per kg of live market pig was 3.39 kg CO_2-eq, and the contribution by feed production, enteric fermentation, manure management and farm energy consumption to CF was 55%, 4%, 28% and 13%, respectively. According to the documented studies, the contribution by feed production varied from 49% for North America (MacLeod et al., 2013) to 83% for aggregated pig production system in Sichuan province, China (Luo et al., 2015). Jianyi et al. (2015) also found the relative contribution by feed production to CF per kg of pork decreased from 50.9% in 1979 to 33.2% in 2009.

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

Manure management is the second largest emission source next to feed production, accounting for 28% of the total CF. The relative contribution of manure management varied from 12% to 41% in the documented studies. Luo et al. (2015) found manure management contributed only 12% of the total GHG emissions from the system when assessing CF of pork supply chain in Sichuan, China. Lesschen et al. (2011) found manure management contributing 41% to total CF when making assessment of CF of EU-27 pork supply chain.

Feed Production

GHG emissions from feed production are mainly derived from feed crop planting, feed processing, and feed transportation. The emissions from crop planting accounted for 66% of CF of feed production, whereas feed processing and transportation shared the remaining 34%.

Feed Crop Planting

Because of different planting measures, the CF magnitude and compositions for different feed materials were also different. CF of corn, soybean meal and wheat bran was 0.51, 0.12, 0.53 kg CO_2-eq/kg, respectively. As shown by the data in Fig. 2, emissions from nitrogen fertilizer application accounted for the majority of the total CF, i.e., 44%, 41% and 33% for corn, soybean meal and wheat bran, respectively. The lower contribution of nitrogen fertilizer application in wheat bran production results from the larger amount of water used in wheat irrigation. Compared with the global average of 28% relative contribution of nitrogen fertilizer application for feed production (MacLeod et al., 2013), the higher value of the current study was mainly due to larger nitrogen fertilizer input for Chinese crops (Zhang et al., 2013).

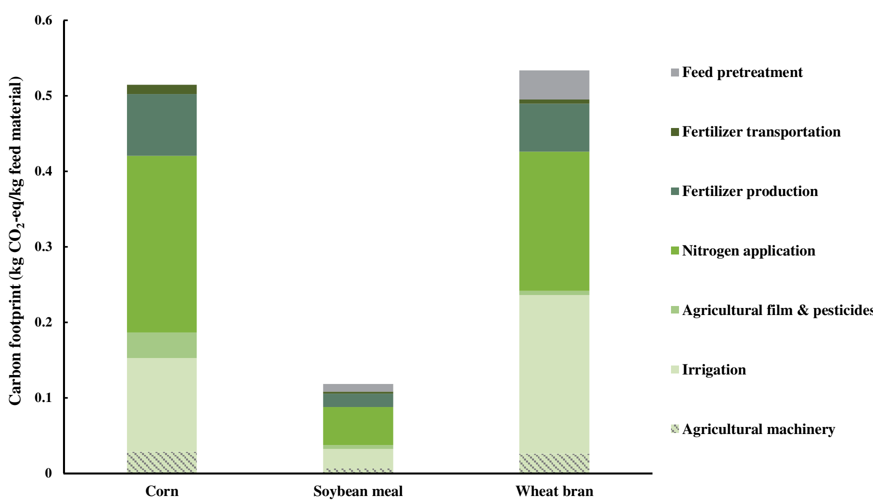

Fig. 2. Partitioning of carbon footprint of feed materials by production component.

It is an important way to reduce CF of crops by reducing nitrogen fertilizer application rationally based on crop nutrient requirements (Jianyi et al., 2015; Ju et al., 2009). In this study, the application amount of nitrogen fertilizer in corn and wheat was 209 kg/hm^2 and 216 kg/hm^2, respectively, which were significantly higher than the amount applied for corn in America (152 kg N/hm^2) (Grassini and Cassman, 2012). The Good Agricultural Practice for EU recommended the maximum N fertilization rate for corn and wheat to be 75-180 kg/hm^2 and 80-210 kg/hm^2, respectively (European Union Regulations, 2014). Assuming nitrogen fertilizer application of corn and wheat is reduced to the EU-recommended class II value of 140 kg/hm^2 for corn and 180 kg/hm^2 for wheat, GHG emissions from nitrogen fertilizer application of corn and wheat will be reduced by 33% (7,652 t CO_2-eq & 5,136 t CO_2-eq) and 17% (1,141 t CO_2-eq & 951 t CO_2-eq), respectively. The proportion of emissions from nitrogen fertilizer applied for corn and wheat in total emissions from crop planting will be decreased by 7% (from 44% to 37%) and 3% (from 33% to 30%), respectively. These reductions translate to 3,628 t CO_2-eq lower annual GHG emissions. Accordingly, the CF per kg of live market pig would fall from 3.39 kg CO_2-eq to 3.16 kg CO_2-eq, a reduction of nearly 7%.

Feed Transportation

The feed transport distance directly affects CF of feed production and animal production system. In this study, emissions from long-distance transport (300-500 km) of feed raw materials contributed 31% of the feed production or 17% of the total CF because the corn and soybean meal involved are from other provinces. Pork CF assessment of household and aggregated farms in Sichuan province, China showed that a feed transportation CF of 0.01 kg CO_2-eq/kg LW (Luo et al., 2015), which is much lower than 0.57 kg CO_2-eq/kg LW obtained in the our current study. Noya et al. (2016) found that feed transportation accounted for 17% of total GHG emissions from feed production due to the large distances between growing areas of ingredients and feed processing plants in Spanish pig production chain. A similar result (4%-17%) was reported for the Portuguese pork supply chain (González-García et al., 2015).

Shortening transport distance and reducing the number of no-load transport vehicles are other important ways to reduce CF of pig production. In this case study, transport distance of corn and soybean meal between the feed origin and the swine farm was 325 km and 495 km, respectively, and each round of feed raw materials transport involved empty vehicle to the feed-origin area, resulting in an annual GHG emission of 9,989 t CO_2-eq for feed transportation. If using one-way transport distance of 325 km with full load for soybean meal and 495 km for corn (Fig. 3b), the GHG emissions from feed transportation will be reduced to 5,957 t CO_2-eq. The resultant contribution to feed production of this emission source will be reduced from 31% to 18%, and CF of per kg live market pig will be reduced by 9% to 3.07 kg CO_2-eq. If using two-way transport distance of 30 km with load for corn and soybean meal (Fig. 3c), the GHG emissions from feed transport will be reduced to 921 t CO_2-eq, and the relative contribution to feed production will be reduced to 4%. The corresponding CF of pork will be reduced by 17% to 2.81 kg CO_2-eq/kg LW. Finally, if using one-way load with transport distance of 30 km corn for and soybean meal (Fig. 3d), GHG emissions from feed transport will be reduced to 549 t CO_2-eq, and the relative contribution to feed production reduced to only 2% of CF. The overall CF will be reduced to 2.78 kg CO_2-eq/kg LW, 18% lower than the baseline scenario. Thus, obtaining feedstocks from regions within 30 km of the pig farm and avoiding empty vehicles could reduce 9%-18% total CF of the pig supply chain.

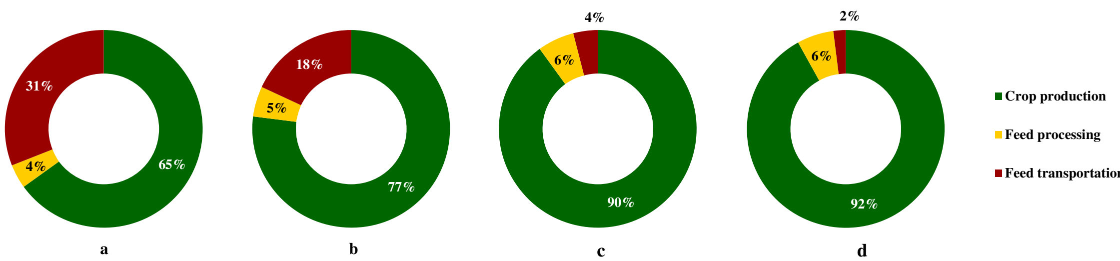

Fig. 3. Comparison of carbon footprint from feed production for four transportation scenarios: (a) two-way load (one way at full-load and one way empty) with a transport distance of 650 km for corn and 990 km for soybean meal; (b) one-way at full-load with a transport distance of 325 km for corn and 495 km for soybean meal; (c) two- way load (one way at full-load and one way empty) with a transport distance of 60 km for corn and soybean meal; and (d) one-way load with a transport distance of 30 km for corn and soybean meal.

Manure Management

Manure management included three storage stages, i.e. in-house storage, outdoor storage, and manure application on the farmland. Because GHG emissions from manure application during the stage of feed crop planting has already been included in the CF calculation, to avoid double counting, emissions from manure application on farmland were not included. CF of the manure management stage was 1.04 kg CO_2-eq/kg LW, and CF for in-house emissions and outdoor manure treatment accounted for 16% and 84% of the manure management CF, respectively (Fig. 4).

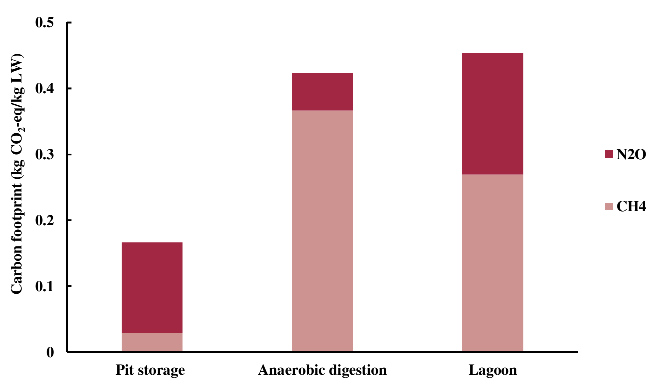

Fig. 4. Carbon footprint of manure management (CH_4 emission from anaerobic digestion results from leakage of the biogas digestion system).

This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.
The DOI for this manuscript is https://doi.org/10.13031/trans.12805. It will remain the same after publication.

In-house Manure Management

Emissions from in-house manure included CH_4 and N_2O emissions from pig manure storage. GHG emitted from animal house contributed only 4% of the total CF at 0.16 kg CO_2-eq/kg LW (Fig. 4). The main reason for the smaller value is the short- time storage. The manure of sows and nursery pigs was collected in pit and stored for 5 days, whereas manure of fattening pigs was collected and removed daily.

N_2O emissions from manure management is closely related to Nex rate of the pigs. A low crude protein diet plays an important role in reducing Nex of pigs and N-related gaseous emissions of manure management (Wang et al. 2017). In this study, the value of Nex used to calculate N_2O emissions from manure management was based on the emission factors published in China. Nex rate of fattening pig, nursery pig and sow was 33, 20 and 44 g N/head/day, respectively. Compared with the default values of Nex in IPCC (29 g N/head/day for fattening pig, 11 g N/head/day for nursery pig, 51 g N/head/day for sow), Nex coefficient of fattening pig and nursery pig in our study was, respectively, 12% and 45% higher, but 15% lower for sows. Osada et al. (2011) and Ogino et al. (2013) showed if crude protein content in diet reduced to 85%, Nex would reduce by more than 20%. Low-protein diets reduce the use of soy-based feedstuffs while slightly increasing usage of cereals or synthetic amino acids. But GHG emissions from feed production show a downward trend. If the Nex rate of fattening and nursery pigs in our study is reduced to the IPCC default value by reducing the dietary crude protein content, the proportion of emissions related to Nex in manure management will be reduced by 15%.

Outdoor Manure Management

Emissions from outdoor manure storage contributed 24% of the total CF at 0.42 kg CO_2-eq/kg LW for the anaerobic digestion and 0.44 kg CO_2-eq/kg LW for the lagoon (Fig. 4). In this study, manures was collected firstly for using anaerobic digestion to produce biogas and then CH_4 was recovered and used for biogas generation. In order to explore mitigation potentials for manure management, GHG emissions from the traditional manure treatment of pit storage – lagoon (baseline scenario A) was compared with the manure management practices (scenario B) in this study (Table 7).

Table 7 Comparison of GHG emissions (t CO_2-eq/yr) from two types of manure management.

Source	Scenario A (pit storage-lagoon)	Scenario B (pit storage-anaerobic digestion-lagoon)	% reduction by Scenario B
Pit storage	2,617	2,617	0
Anaerobic digestion	--	6,638	N/A
Lagoon	43,300	7,110	84
Power consumption of biogas engineering	--	654	N/A
Methane generation	--	-5,845	N/A
Total	45,918	11,174	76

Table 7 shows that GHG emissions from manure management stage of baseline scenario A totaled 45,918 t CO_2-eq/yr.

Emissions from lagoon accounted for 94%. CF of pig production system was 5.27 kg CO_2-eq/kg LW under the traditional manure treatment. In scenario B, emissions form the manure management stage is reduced by 34,744 t CO_2-eq/yr because of the anaerobic digestion treatment before lagoon storage. GHG emissions of manure management is reduced by 76% after anaerobic fermentation. Compared with manure without anaerobic treatment, CH_4 emissions from manure is reduced by 75% because of anaerobic digestion and the recycle of biogas. It is lower than the modeled reduction rate of 90% CH_4 emissions by Sommer et al. (2004). The digested manure can increase the amount of direct nitrogen available to plants and reduce the amount of synthetic fertilizer requirement, which can reduce CF of feed production (Holm-Nielsen et al., 2009; Weiland, 2010). As an effective CF mitigation measure, anaerobic digestion is one of the recommended manure management practices in China, as stated in "Thirteenth Five-Year Biogas Development Plan" jointly issued by the China National Development and Reform Commission and the Ministry of Agriculture. The total investment in rural biogas projects will be 50 billion yuan (RMB) during the “Thirteenth Five-Year National Strategic Plan” period. The number of biogas in China was 113,182 in 2015 (NAC, 2016). UASB (Up-flow Anaerobic Sludge Bed), CSTR (Continuous Stirred Tank Reactor) and USR (Upflow Solid Reactor) are common types of animal manure anaerobic digesters in China. The produced biogas is used as fuel for heating and/or electric power generation, with the generated electricity integrated into the national electric power grid.

CONCLUSION

This case study employed LCA to estimate carbon footprint (CF) of a large-scale pig production chain based on the actual production conditions in Northern China. It also identified the potential areas for mitigating CF. The results showed that CF of a large-scale pig production chain in Northern China is 3.39 kg CO_2-eq/kg LW. The relative contributions to the total CF were 55% for feed production (including crop planting and feed processing transportation), 28% for manure management, 13% for farm energy consumption, and 4% for enteric fermentation. Nitrogen fertilizer application and feedstuffs transportation were key sources of GHG emissions for feed production. Compared to traditional manure management practices (pit storage – lagoon), anaerobic digestion treatment of manure and recycling of CH_4, as used in this case study, can reduce CF of the pig supply chain by 76% .

ACKNOWLEDGEMENTS

This study was supported by the Non-Profit Research Foundation for Agriculture (201303091), China Agriculture Research System (CARS-35).

REFERENCES

Bai, Z., Ma, L., Qin, W., Chen, Q., Oenema, O., Zhang, F., 2014. Changes in pig production in China and their effects on nitrogen and phosphorus use and losses. *Environmental science & technology* 48(21), 12742-12749. https://doi.org/10.1021/es502160v

Basset-Mens, C., Van der Werf, H.M., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. *Agriculture, Ecosystems & Environment* 105(1), 127-144. https://doi.org/10.1016/j.agee.2004.05.007

Bi, Y., Gao, C., Wang, Y., Li, B., 2009. Estimation of Straw Resources in China. Transactions of the Chinese Society of Agricultural Engineering, pp. 211-217 (In Chinese). https://doi.org/10.3969/j.issn.1002-6819.2009.12.037

Cederberg, C., 2004. Environmental assessment of future pig farming systems: quantifications of three scenarios from the FOOD 21 synthesis work. SIK Institutet för livsmedel och bioteknik.

Chen, S., Lu, F., Wang, X., 2015. Estimation of greenhouse gases emission factors of China's nitrogen, phosphate and potash fertilizers. *Acta Ecologica Sinica* 35(19), 6371-6383 (In Chinese). https://doi.org/10.5846/stxb201402210304

China National Environmental Protection Agency, 2010. The First National Pollution Census Bulletin of The People's Republic of China 2010. *China Statistics Press*, Beijing (In Chinese).

Dalgaard, R., Halberg, N., Hermansen, J.E., 2007. Danish pork production: an environmental assessment. Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet.

de Vries, M., de Boer, I.J., 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock science* 128(1), 1-11. https://doi.org/10.1016/j.livsci.2009.11.007

European Union (Good Agricultural Practice for Protection of Waters) Regulations 2014. Statutory instruments. S.I. 31 of 2014.

González-García, S., Belo, S., Dias, A.C., Rodrigues, J.V., da Costa, R.R., Ferreira, A., de Andrade, L.P., Arroja, L., 2015. Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options. *Journal of Cleaner Production* 100, 126-139. https://doi.org/10.1016/j.jclepro.2015.03.048

Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. *Proceedings of the National Academy of Sciences* 109(4), 1074-1079. https://doi.org/10.1073/pnas.1116364109

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. *Bioresource technology* 100(22), 5478-5484. https://doi.org/10.1016/j.biortech.2008.12.046

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

IPCC, 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

ISO, 2006. 14044: Environmental Management - Life Cycle Assessmentd - equirements and Guidelines. International Organization for Standardization

Jianyi, L., Yuanchao, H., Shenghui, C., Jiefeng, K., Lilai, X., 2015. Carbon footprints of food production in China (1979–2009). *Journal of Cleaner Production* 90, 97-103. https://doi.org/10.1016/j.jclepro.2014.11.072

Ju, X.-T., Xing, G.-X., Chen, X.-P., Zhang, S.-L., Zhang, L.-J., Liu, X.-J., Cui, Z.-L., Yin, B., Christie, P., Zhu, Z.-L., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences* 106(9), 3041-3046. https://doi.org/10.1073/pnas.0813417106

Kool, A., Blonk, H., Ponsioen, T., Sukkel, W., Vermeer, H., de Vries, J., Hoste, R., 2009. Carbon footprints of conventional and organic pork: assessments of typical production systems in the

Netherlands, Denmark, England and GermanyCarbon footprints of conventional and organic pork: assessments of typical production systems in the Netherlands, Denmark, England and Germany. Blonk Milieu Advies [etc.].

Lesschen, J., Van den Berg, M., Westhoek, H., Witzke, H., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology* 166, 16-28. https://doi.org/10.1016/j.anifeedsci.2011.04.058

Lineng, C., Hong, L., Zhanfeng, X., 2003. Research on the math models of the combustion oil consumption of the farm transport machineries. *Journal of Zhejiang University* 29(2), 185-187 (In Chinese). https://doi.org/10.3321/j.issn:1008-9209.2003.02.017.

Luo, T., Yue, Q., Yan, M., Cheng, K., Pan, G., 2015. Carbon footprint of China's livestock system–a case study of farm survey in Sichuan province, China. *Journal of Cleaner Production* 102, 136-143. https://doi.org/10.1016/j.jclepro.2015.04.077

MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Vellinga, T., Henderson, B., Steinfeld, H., 2013. Greenhouse gas emissions from pig and chicken supply chains–A global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.

Ministry of Agriculture of China, 2016. China Agriculture Statistical Report 2016. *China Agriculture Press*, Beijing (In Chinese).

National Bureau of Statistics, 2016. China Energy Statistical Yearbook 2016. *China Statistics Press*, Beijing (In Chinese).

National Development and Reform Commission of China, 2016. National Data Compilation of Revenue and Cost of Agricultural Products 2016. *China Statistics Press*, Beijing (In Chinese).

National Development and Reform Commission of China, 2013. The People's Republic of China Second National Communication on Climate Change 2013. *China Economic Press*, Beijing (In Chinese).

Nasir, I.M., Mohd Ghazi, T.I., Omar, R., 2012. Anaerobic digestion technology in livestock manure treatment for biogas production: a review. *Engineering in Life Sciences* 12(3), 258-269. https://doi.org/10.1002/elsc.201100150

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2011. Environmental assessment of Danish pork.

Noya, I., Aldea, X., Gasol, C.M., González-García, S., Amores, M.J., Colón, J., Ponsá, S., Roman, I., Rubio, M.A., Casas, E., 2016. Carbon and water footprint of pork supply chain in Catalonia: From feed to final products. *Journal of environmental management* 171, 133-143. https://doi.org/10.1016/j.jenvman.2016.01.039

Ogino, A., Osada, T., Takada, R., Takagi, T., Tsujimoto, S., Tonoue, T., Matsui, D., Katsumata, M., Yamashita, T., Tanaka, Y., 2013. Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids. *Soil science and plant nutrition* 59(1), 107-118. https://doi.org/10.1080/00380768.2012.730476

Osada, T., Takada, R., Shinzato, I., 2011. Potential reduction of greenhouse gas emission from swine manure by using a low-protein diet supplemented with synthetic amino acids. *Animal feed science and technology* 166, 562-574. https://doi.org/10.1016/j.anifeedsci.2011.04.079

Pelletier, N., Lammers, P., Stender, D., Pirog, R., 2010. Life cycle assessment of high-and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. *Agricultural Systems* 103(9), 599-608. https://doi.org/10.1016/j.agsy.2010.07.001

Reckmann, K., Traulsen, I., Krieter, J., 2013. Life Cycle Assessment of pork production: A data inventory for the case of Germany. *Livestock Science* 157(2), 586-596. https://doi.org/10.1016/j.livsci.2013.09.001

Sommer, S.G., Petersen, S.O., Møller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutrient Cycling in Agroecosystems* 69(2), 143-154. https://doi.org/10.1023/B:FRES.0000029678.25083.fa

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., de Haan, C., 2006. Livestock's long shadow: environmental issues and options. Food & Agriculture Org.

Vergé, X., Maxime, D., Desjardins, R., VanderZaag, A., 2016. Allocation factors and issues in agricultural carbon footprint: a case study of the Canadian pork industry. *Journal of Cleaner Production* 113, 587-595. https://doi.org/10.1016/j.jclepro.2015.11.046

Wang, Y., Dong, H., Zhu, Z., Gerber, P.J., Xin, H., Smith, P., Opio, C., Steinfeld, H., Chadwick, D., 2017. Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A System Analysis. *Environmental Science & Technology* 51(8), 4503-4511. https://doi.org/10.1021/acs.est.6b06430

Wang, Z., Wang, M., Chen, F., 2015. Carbon footprint analysis of crop production in North China Plain. *Scientia Agricultura Sinica* 48(1), 83-92 (In Chinese). https://doi.org/10.3864/j.issn.0578-1752.2015.01.09

Weiland, P., 2010. Biogas production: current state and perspectives. *Applied microbiology and biotechnology* 85(4), 849-860. https://doi.org/10.1007/s00253-009-2246-7

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems & Environment* 149, 124-134. https://doi.org/10.1016/j.agee.2011.12.015

Wiedemann, S., McGahan, E.J., Murphy, C.M., 2016. Environmental impacts and resource use from Australian pork production assessed using life-cycle assessment. 1. Greenhouse gas emissions. *Animal Production Science* 56(9), 1418-1431. https://doi.org/10.1071/AN15881

Xu, X., Lan, Y., 2016. A comparative study on carbon footprints between plant-and animal-based foods in China. *Journal of Cleaner Production* 112, 2581-2592. https://doi.org/10.1016/j.jclepro.2015.10.059

Zhang, W.-f., Dou, Z.-x., He, P., Ju, X.-T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.-L., Zhang, Y., Wu, L., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proceedings of the National Academy of Sciences* 110(21), 8375-8380. https://doi.org/10.1073/pnas.1210447110

Zhang, W., Lang, Q., Wu, S., Li, W., Bah, H., Dong, R., 2014. Anaerobic digestion characteristics of pig manures depending on various growth stages and initial substrate concentrations in a scaled pig farm in Southern China. *Bioresource technology* 156, 63-69. https://doi.org/10.1016/j.biortech.2014.01.013